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Evaluation of Propeller Unsteady Force Codes for Noncavitating Conditions

by

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14. ABSTRACT

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There were few consistent trends in the comparisons of calculations to measurements, and no one code stood out as being significantly better than the others for most test cases. PUF-2 and PROPCAV were a little better on average than the other codes for predicting blade frequency thrust and torque. The codes that used an inclined shaft wake model (PUF-2IS and MPUF-3A) were not consistently better at predicting blade loads than codes that did not use an inclined shaft wake model (PUF-14 and PROPCAV), for Propellers 4661 and 5168 on inclined shafts. MPUF-3A and PROPCAV were better overall than the other codes for predicting the first harmonic amplitudes, for propellers on an inclined shaft.

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NOMENCLATURE

A_E	Expanded area of propeller blades
A_o	Propeller disk area, πR^2
C_f	Flat plate friction coefficient or ITTC model-ship correlation line
C/M	Calculated amplitude divided by measured amplitude of force or moment
C-M	Calculated phase minus measured phase of force or moment
C_{Th}	Thrust loading coefficient, $C_{Th} = \frac{T}{\frac{1}{2}\rho V_A^2 A_o}$
c	Chord length of blade section
D	Propeller tip diameter
F	Force or moment
$\overline{F}$	Mean force or moment
$\hat{F}_n$	Amplitude of nth harmonic of force or moment
F_x, F_y, F_z	Components of force for one blade in the rotating PUF-2 coordinate system. Nondimensional on $\rho n^2 D^4$ and positive in the directions of the positive x, y, and z axes.
F_{x1}, F_{y1}, F_{z1}	Amplitudes of first harmonic for F_x, F_y, and F_z.
i_T	Total rake of midchord
J	Advance coefficient based on volume mean speed of advance, $J = \frac{V_A}{nD}$
k	Reduced frequency of unsteady force, $k = \omega c / 2V_{rel}$
M_x, M_y, M_z	Components of moment for one blade in the rotating PUF-2 coordinate system. Nondimensional on $\rho n^2 D^5$ and positive for right hand rotation about the positive x, y, and z axes. M_x is the shaft torque and M_y is the spindle torque.
M_{x1}, M_{y1}, M_{z1}	Amplitudes of first harmonic for M_x, M_y, and M_z.
n	Shaft speed in revolutions per second or harmonic number
O(2)	Second order accuracy
O(4)	Fourth order accuracy
P	Pitch of blade section
R	Propeller tip radius

R_n	Reynolds number of blade section, $R_n = \frac{V_{rel}c}{\nu}$
r_h	Hub radius
T	Thrust
t	Time or maximum thickness of blade section
V_A	Volume mean speed of advance
V_{rel}	Velocity relative to blade section
x, y, z	The coordinate axes following PUF-2 conventions. For the nonrotating coordinate system, x is positive aft, y is positive up, and z is positive to port. The rotating axes coincide with the nonrotating axes when the blade is at top dead center (θ_p=0). The rotating y-axis is the spindle axis.
Z	Number of propeller blades
θ_m	Projected skew angle of midchord
θ_p	Angle of key blade from vertical, positive clockwise when looking forward
ν	Kinematic viscosity of water
ρ	Mass density of water
ϕ	Perturbation velocity potential
ϕ_n	Phase angle of nth harmonic of force or moment, degrees
ω	Angular frequency of unsteady force, rad/sec

ABBREVIATIONS

AIAA	American Institute of Aeronautics and Astronautics
ATTC	American Towing Tank Conference
BEM	Boundary Element Method
BF	Blade Frequency (eg. 2xBF is twice blade frequency)
BVP	Boundary Value Problem
CRP	Controllable-Reversible Pitch
DTNSRDC	David Taylor Naval Ship Research and Development Center, now NSWCCD
DTRC	David Taylor Research Center, now NSWCCD
FP	Fixed Pitch
ITTC	International Towing Tank Conference

LH	Left Hand rotation of propeller
LU	Lower and Upper triangular matrices
MIT	Massachusetts Institute of Technology
MPUF-3A	A VLM code for calculating unsteady forces on cavitating propellers, developed by MIT and UT/Austin
NSRDC	Naval Ship Research and Development Center, now NSWCCD
NSWCCD	Naval Surface Warfare Center, Carderock Division
PROPCAV	A BEM code for calculating unsteady forces on cavitating propellers, developed by MIT and UT/Austin
PUF-2	A VLM code for calculating unsteady forces on noncavitating propellers, developed by MIT
PUF-2IS	The version of PUF-2 that has an inclined shaft wake model.
PUF-10	A BEM code for calculating unsteady forces on noncavitating propellers, developed by MIT
PUF-14	A VLM code for calculating unsteady forces on noncavitating propellers, developed by MIT
RANS	Reynolds Averaged Navier-Stokes code
RH	Right Hand rotation of propeller
SF	Shaft frequency
SNAME	The Society of Naval Architects and Marine Engineers
TDC	Top Dead Center
UT/Austin	University of Texas at Austin
VLM	Vortex Lattice Method

U.S. CUSTOMARY UNITS AND METRIC EQUIVALENTS

U.S. CUSTOMARY	METRIC
1 degree (angle)	0.01745 radians
1 degree Fahrenheit	$5/9*(F-32)$= Celsius
1 foot	0.3048 meters
1 horsepower	0.7457 kilowatts
1 pound force	4.448 Newtons
1 slug	14.59 kilograms

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ABSTRACT

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There were few consistent trends in the comparisons of calculations to measurements, and no one code stood out as being significantly better than the others for most test cases. PUF-2 and PROPCAV were a little better on average than the other codes for predicting blade frequency thrust and torque. The codes that used an inclined shaft wake model (PUF-2IS and MPUF-3A) were not consistently better at predicting blade loads than codes that did not use an inclined shaft wake model (PUF-14 and PROPCAV), for Propellers 4661 and 5168 on inclined shafts. MPUF-3A and PROPCAV were better overall than the other codes for predicting the first harmonic amplitudes, for propellers on an inclined shaft.

ADMINISTRATIVE INFORMATION

INTRODUCTION

The objective of this investigation is to identify the best code for calculating the unsteady forces and moments on surface ship propellers during noncavitating operating conditions.

Design requirements for surface ship propellers include restrictions on blade loading when the propeller is not cavitating. Restrictions are typically imposed on the unsteady thrust and torque at blade frequency and twice blade frequency. For controllable pitch propellers, the mean spindle torque must be slightly positive so that the blades will move to a positive pitch angle if the pitch control mechanism fails. The positive pitch angle allows the propeller to produce positive thrust for propulsion. Restrictions are also imposed on the mean and unsteady spindle torque, so that the loads transmitted to the pitch control mechanism will be sufficiently low to avoid a failure of the mechanism.

Propeller designers need accurate methods to predict spindle torque and unsteady forces, in order to meet the design requirements. Previous validation studies [1, 2, 3] concluded that PUF-2 was the best code for calculating unsteady forces, and PUF-2 has been used extensively. However, new unsteady force codes are now available, and the new codes need to be evaluated. Unsteady force codes currently available for noncavitating operating conditions include PUF-2 [4, 5], PUF-10 [6, 7], and PUF-14 [8] from the Massachusetts Institute of Technology. There are some other unsteady force codes that were developed to predict cavitation that can also be used for noncavitating flows. These codes include include MPUF-3A [9, 10] and PROPCAV [11, 12, 13, 14] from the University of Texas at Austin. PROPCAV is an extension of the MIT code PUF-10 [6, 7], so PUF-10 is not included in the present study.

Black[*] evaluated most of these new codes in 1998. He calculated unsteady forces using PUF-2, PUF-10, PUF-14, and MPUF-3A for three propellers, and compared the calculated forces to measurements. He looked at blade frequency thrust and torque for an axial wake and shaft frequency forces and moments for inclined shafts. No code was clearly better than the others for the calculation of amplitudes. The phases were predicted most accurately by PUF-2 for the axial wake and by PUF-14 for the inclined shafts. MPUF-3A was developed from PUF-2, so it was expected that the MPUF-3A results should be close to the PUF-2 results. However, there were differences between the MPUF-3A and PUF-2 results that couldn't be explained.

It is necessary to update the 1998 validation study of Black, for several reasons. PUF-10 has been replaced by PROPCAV, and the accuracy of PROPCAV needs to be determined for noncavitating operating conditions. The accuracy of MPUF-3A for predicting the 1/rev loads needs to be determined, since that was not included in the 1998

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[*] Black, S.D., "Unsteady Propeller Code Validation", Minutes of SNAME Panel H-8 Propulsion Hydrodynamics, Meeting 108, Arlington, VA (September 10, 1998).

study. The accuracy of the codes for predicting spindle torque also needs to be determined, since spindle torque was not included in the 1998 study and new spindle torque data[*] have recently become available.

MPUF-3A has undergone several revisions since the 1998 study. However, the only revisions that may affect the noncavitating forces and moments are believed to be the modification of the hub model to allow for noncylindrical hubs, and a new option for determining the number of revolutions to iterate for convergence. The effect of these revisions needs to be determined.

Some of the codes used in the 1998 study were sensitive to the number of panels. Unsteady force calculations done today typically have more panels than were used in the 1998 study, and using more panels may improve the accuracy.

The present study evaluates the codes PUF-2, PUF-14, MPUF-3A, and PROPCAV. Calculations are compared to measurements for Propeller 4119 operating in a three-cycle axial wake, and Propellers 4661, 4990, and 5168 on inclined shafts. The mean loads, shaft frequency loads, and blade frequency loads are examined.

PROPELLER CODES

The versions of the codes evaluated in this study and references describing their solution methods are identified in Table 1. PUF-2 is a vortex lattice code that is older than the other codes and has been used more extensively. PUF-2 was developed by MIT for axial flows, and a special version of the code was later developed to account for the effects of an inclined shaft on the trailing vorticity. PUF-14 is another vortex lattice code that was developed by MIT for the purpose of calculating the body forces for use in a Reynolds Averaged Navier-Stokes RANS code.

MPUF-3A is a vortex lattice code that was developed by MIT and UT/Austin for the purpose of predicting cavitation. MPUF-3A originally began as a modification to PUF-2, but the modifications are now extensive enough so that MPUF-3A is no longer equivalent to PUF-2 for noncavitating flows.

PROPCAV is a potential-based boundary element method (BEM) that was developed by MIT and UT/Austin for the purpose of predicting cavitation. PROPCAV began as an extension of PUF-10 and now supercedes PUF-10.

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[*] Measurements in the NSWCCD 36-inch water tunnel by Martin Donnelly.

Table 1. Versions of the codes being evaluated.

Code	Version	Release Date	References
PUF-2	2.1	January 31, 1987	4, 5
PUF-14	14.3	April 5, 2000	8
MPUF-3A	2.1.1	January 2004	9, 10
PROPCAV	2.1.1[*]	January 2004	6, 7, 11, 12, 13, 14

The theories and numerical approximations used by the codes are summarized in Tables 2 through 5. All evaluations of the codes are limited to deeply submerged open propellers without cavitation. Coupling to a RANS code or Euler solver is not evaluated.

PUF-2 is the code traditionally used for calculating noncavitating unsteady forces, and MPUF-3A and PROPCAV are codes that were developed more recently for calculating cavitation. PUF-2 has a more accurate finite difference scheme for calculating the apparent mass force[†], which would tend to make PUF-2 more accurate for the higher frequencies of unsteady forces. However, MPUF-3A and PROPCAV have several other features that should give them an overall advantage over PUF-2. These features include a more realistic trailing vortex wake model, cosine and half-cosine spacing of panels on the blades, models for the coupling between thickness and loading, and inclusion of the hub. MPUF-3A also allows a finer spacing on the nonkey blades. PROPCAV is the only code that allows the sources representing blade thickness to have unsteady strengths.

PUF-14 has several theoretical advantages over PUF-2, as shown in Tables 2 through 5. One apparent advantage is that PUF-14 is the only code that allows the inflow to vary axially. However, PUF-14 does not have an inclined shaft wake model that can be used without coupling to a RANS code, and the effects of wake asymmetries due to shaft inclination are known to be important. PUF-14 requires more memory and execution time than PUF-2, because PUF-14 solves the boundary value problem on all blades

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[*]   Version 2.1.1 of PROPCAV was modified by Scott Black of NSWCCD to print the separate contributions of blade and hub loading.

[†]   According to Kinnas and Fine [11], PROPCAV uses a 4th order backward difference scheme to evaluate the time derivative of velocity potential. However, examination of subroutine DPOTDT indicates that PROPCAV actually uses a 2nd order central difference scheme.

simultaneously. PUF-14 has received little use outside of RANS coupling problems, because the execution times are longer, the preparation of input is more involved, and PUF-14 has not been consistently more accurate than PUF-2 based on the limited number of validation runs done previously[*].

Table 2. Formulation of boundary value problem and its solution.

	PUF-2	PUF-14	MPUF-3A	PROPCAV
Boundary Conditions:				
Blade sections	cylindrical	cylindrical or noncylindrical	cylindrical or noncylindrical	cylindrical
Hub	no	images	images	panels
Duct	no	images	images	no
Inflow varies axially	no	yes	no	no
Viscous pitch correction	yes	no	yes	yes
Solution to BVP:				
Where BVP is solved	on key blade	on all blades simultaneously	on key blade	on key blade
Kutta condition	explicit, one point linear	implicit, control point at trailing edge	---	explicit, iterative pressure
Thickness-loading coupling	no	no	yes	yes
Matrix solver	LU decomposition	LU decomposition	LU decomposition	block iterative

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[*] Black, S.D., "Unsteady Propeller Code Validation", Minutes of SNAME Panel H-8 Propulsion Hydrodynamics, Meeting 108, Arlington, VA (September 10, 1998).

Table 3. Approximations to vortices and sources on blades.

	PUF-2	PUF-14	MPUF-3A	PROPCAV
Type of paneling	vortex & source lattice	vortex & source lattice	vortex & source lattice	dipole & source surface panels
Allows fine grid on nonkey blades & wakes	no	yes	yes	---
Spacing across span	uniform	uniform, half-cosine, cosine	uniform, half-cosine, cosine	uniform, half-cosine, cosine
Spacing across chord	uniform	cosine	half-cosine, cosine	uniform, cosine
Separation of trailer at tip	distance estimated empirically	neglected	tip flow angle estimated	tip vortex cavity model
Strength of sources representing blade thickness	steady	steady	steady	unsteady

Table 4. Approximations to vorticity in wake.

	PUF-2	PUF-14	MPUF-3A	PROPCAV
Type of paneling	vortex lattice	vortex lattice	vortex lattice	dipole panels
Wake alignment includes shaft inclination	yes	no	yes	yes
Trailers merge together continuously at roll up points	yes	no	no	no
Strength of shed vortices decays due to dissipation	yes	yes	---	---
Method used for wake alignment	empirical, wake pitch does not vary as blade rotates	aligned with mean velocities	aligned with mean velocities	aligned with either mean or local velocities

Table 5. Methods used to calculate blade forces.

	PUF-2	PUF-14	MPUF-3A	PROPCAV
Force due to bound vorticity	Kutta-Joukowski law	Kutta-Joukowski law	integrate pressure	integrate pressure
Pressure force due to $\rho\, \partial\phi/\partial t$	five point central difference, O(4) accurate	five point central difference, O(4) accurate	---	three point central difference, O(2) accurate
Viscous drag coefficient	uniform	varies radially	varies radially	uniform
Force due to sources	Lagally's theorem	neglected	integrate pressure	integrate pressure
Leading edge suction force correction	yes	yes	---	yes

TEST CASES

The test cases under consideration include various combinations of fixed pitch (FP) propellers, controllable-reversible pitch (CRP) propellers, nonuniform axial wakes due to upstream screens, and tangential wakes due to shaft inclination. The geometry and operating conditions of the propellers are summarized in Tables 6 and 7, and the propellers are illustrated in Figure 1.

Propeller 4119 is a research propeller that was designed [15] to have optimum loading in open water. Unsteady thrust and torque were measured [3] in the NSWCCD 24 inch water tunnel when the three-bladed propeller was operating behind harmonic wake screens having 3, 6, 9, and 12 cycles/revolution. Jessup [3] believes that blade resonances have affected the measurements for the 12th shaft harmonic, so shaft harmonics of 12 and above are not considered.

Propeller 4661 has left-hand rotation and was designed for a twin screw ship that has a transom stern with open shafts and struts. The loads on a single blade were measured [1] at the NSWCCD tow tank on Carriage 2. The propeller was advancing in open water and was driven from downstream on an inclined shaft. Tests were run for shaft angles of 10, 20, and 30 degrees. The 10 degree shaft angle was chosen as the test case for this investigation, because 10 degrees is typical of the shaft angles found on ships. A horizontal plate was placed approximately 2.4 diameters above the propeller tips

to suppress any possible effects of the free surface on the blade loads. The nominal wake was measured (Wake 16) and used in the calculations.

Propellers 4990 and 5168 have left-hand rotation and were designed for a twin screw ship that has a transom stern with open shafts and struts. The spindle torque on one blade was measured[*] in the NSWCCD 36 inch water tunnel when the propellers were mounted on a shaft that was inclined 8.9 degrees. The nominal wake had been measured[†] several years earlier than the spindle torque measurements, using a slightly different test set-up. There was a sleeve on the rotating upstream shaft during the wake survey that was not present during the spindle torque measurements. The sleeve increased the diameter of the upstream shaft from approximately 35.1% to 45.1% of the hub diameter. Also, there was a hub extension and shaft present downstream of the propeller for the spindle torque measurements.

PRESENTATION OF RESULTS

All forces and moments are presented using the PUF-2 coordinate system for right-hand propellers. The results for left-hand propellers have been converted to the results of an equivalent right-hand propeller. In the nonrotating coordinate system, x is positive aft, y is positive up, and z is positive to port. The angle θ_p of the key blade is measured from the vertical axis and is positive clockwise looking forward. The rotating coordinate system coincides with the nonrotating coordinate system when $\theta_p=0$. Positive spindle torque M_y would increase blade pitch angle for the equivalent right hand propeller.

The phases of the forces and moments were determined using the following Fourier sine series.

$$F(\theta_p) = \overline{F} + \sum_{n=1}^{\infty} \hat{F}_n \sin(n\theta_p + \phi_n) \tag{1}$$

The comparisons of calculations to measurements are given as amplitude ratios C/M and phase differences C-M. The amplitude ratio C/M is the calculated value of $\overline{F}$ or $\hat{F}_n$

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[*] The spindle torque was measured by Martin Donnelly in 2004 and the data were analyzed by Ian McClintock. The data have not been published at this time.

[†] The wake survey was conducted by Carmen Borda, and the results published in a classified NSWCCD report dated February 1994.

divided by the measured value, and the phase difference C-M is the calculated value of ϕ_n minus the measured value.

Table 6. Geometry of propellers.

Propeller	4119	4661	4990	5168
Type of propeller	FP	CRP	CRP	CRP
Direction of rotation	RH	LH	LH	LH
Tip diameter, D model scale inches	12.000	8.218	15.856	15.856
Hub radius ratio, r_h/R	0.2000	0.3000	0.3000	0.3000
Number of blades, Z	3	5	5	5
Expanded area ratio, A_E/A_o	0.606	0.7303	0.7838	0.8298
Thickness/chord ratio, t/c at 0.7R	0.05418	0.04084	0.06620	0.04874
Skew angle of midchord at tip, θ_m	0°	21.88°	24.74°	16.40°
Total rake/diameter ratio, i_T/D at tip	0.000	0.01029	0.00000	-0.00245
Pitch/diameter ratio, P/D at 0.7R	1.084	1.540	1.719	1.633

Notes:
CRP=Controllable-Reversible Pitch
FP= Fixed Pitch
LH=Left Hand rotation of propeller
RH=Right Hand rotation of propeller

Table 7. Operating conditions.

Propeller	4119	4661	4990	5168
Design advance coefficient, J	0.833	1.140	1.262	1.247
Advance coefficient of test, J	0.833	1.140	1.25	1.25
Design thrust loading coefficient, C_{Th}	0.565	0.448	0.355	0.377
Reynolds number of test, $R_n \times 10^{-5}$	1.23	2.5	38.3	38.6
Reduced frequency, k	1.78 at 1xBF	0.50 at 1xSF	0.469 at 1xSF	0.500 at 1xSF

Notes:
R_n, C_D, and k are given at 0.7R.
BF = Blade Frequency
SF = Shaft Frequency
C_{Th} for Propeller 4661 is from the open water test at design J.

RESULTS OF THE CALCULATIONS

PROPELLER 4119 IN A THREE-CYCLE WAKE

Unsteady thrust and torque were calculated and compared to measurements for the three-bladed Propeller 4119 operating behind a three-cycle wake screen. The amplitude ratios and phase differences for thrust and torque are shown in Figures 2 through 5.

Calculations[*] were done using the grid sizes for the key blade given in Table 8. For the vortex lattice methods (PUF-2, PUF-14, and MPUF-3A), the number of panels across the span is the number of spanwise vortex elements between hub and tip, and the number of panels across the chord is the number of trailing vortex elements between leading edge and trailing edge. For the panel method (PROPCAV), the number of panels across the chord includes the panels on both pressure and suction sides of the blade at a given radius.

Table 8. Grid sizes for Propeller 4119.

	PUF-2	PUF-14	MPUF-3A	PROPCAV
Number of panels across span[†]	18	14	18	20
Number of panels across chord[‡]	20	12	20	40
Number of time steps per revolution	120	60	60	60
Spacing across span	uniform	cosine	half-cosine	half-cosine
Spacing across chord	uniform	cosine	cosine	cosine

The calculated amplitudes deviate the most from measurements for the highest harmonic (3xBF), with PUF-2 and MPUF-3A deviating more than the other codes. Note

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[*] Han-Ch'ing Wang ran PUF-14 for Propeller 4119 and used PSF-2 to calculate the induced velocities on the propeller wake.

[†] The number of panels across the span is input parameter MM for PUF-2, MKEY-1 for PUF-14, MM for MPUF-3A, and MR for PROPCAV.

[‡] The number of panels across the chord is input parameter NN for PUF-2, NKEY for PUF-14, NN for MPUF-3A, and NC for PROPCAV.

that 3xBF corresponds to a reduced frequency k=5.34 at 0.7R. Design requirements for five-bladed surface ship propellers are typically specified through 2xBF which corresponds to a reduced frequency of approximately k=5. Thus, 3xBF for Propeller 4119 is close to the highest frequency usually considered for five-bladed surface ship propellers. The reduced frequencies for all propellers are given in Table 7.

Most codes overpredict thrust and torque amplitudes at 1xBF and 3xBF, and underpredict the amplitudes at 2xBF. MPUF-3A overpredicts the amplitude and underpredicts the phase for most harmonics of thrust and torque. PUF-14 overpredicts the phase for most harmonics.

PROPELLER 4661 ON AN INCLINED SHAFT

Propeller 4661 was mounted on a downstream shaft that was inclined 10 degrees. Shaft inclination produces a strong first harmonic variation in the tangential velocity, so the first harmonic of blade loads were calculated and compared to measurements in Figures 6 and 7. The PUF-14 calculations were done by Black [16], using PSF-3 to calculate the induced velocities on the propeller wake. The grid sizes used in the calculations are given in Table 9.

Table 9. Grid sizes for Propeller 4661.

	PUF-2IS*	PUF-14	MPUF-3A	PROPCAV
Number of panels across span	9	14	18	20
Number of panels across chord	10	12	20	60
Number of time steps per revolution	60	60	60	60
Spacing across span	uniform	cosine	half-cosine	half-cosine
Spacing across chord	uniform	cosine	cosine	cosine

PUF-2IS and PUF-14 underpredict most components of blade loads. MPUF-3A and PROPCAV sometimes overpredict and sometimes underpredict the blade loads. The shaft torque M_x is due to the tangential component of force, which is due mainly to the F_z

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* The PUF-2IS calculations were done by Boswell et al [1]. His report does not give the grid size, but it was common practice at the time to use the values shown in the table for PUF-2IS.

component of force. The amplitudes F_{z1} and M_{x1} are underpredicted by all codes, with PROPCAV giving the best predictions.

Contrary to expectation, the codes that have an inclined wake model (PUF-2IS and MPUF-3A) do not stand out as being consistently better than the codes that do not have an inclined wake model (PUF-14 and PROPCAV). The inclined wake models do not account for the presence of the downstream shaft, which probably forces the tip vortices to stay wrapped around the shaft axis instead of inclining off-axis. The effect of wake inclination on blade loads is evaluated for Propeller 5168 in the next section.

All codes predict the phase closely (within 7 degrees), for Propeller 4661. The differences between calculated and measured phases are smaller for Propeller 4661 than the differences found for Propeller 4119 in Figures 4 and 5. Propeller 4661 has lower reduced frequency than Propeller 4119, as shown in Table 7. Unsteady effects should be less important for Propeller 4661, so the unsteady lift should be more in phase with the quasi-steady lift for Propeller 4661. The reduced importance of unsteady effects for Propeller 4661 may explain why the differences between calculated and measured phases are smaller for Propeller 4661 than Propeller 4119.

It was shown in the previous section that MPUF-3A consistently underpredicted the phase of thrust and torque for Propeller 4119. However, MPUF-3A slightly overpredicts the phase for most of the components shown in Figure 7 for Propeller 4661. MPUF-3A was run with a 20x18 grid on the key blade for the comparison of codes in Figures 6 and 7. MPUF-3A was also run with a 10x9 grid and the results are shown in Figures 8 and 9. The finer grid results in more accurate amplitudes for F_{x1} and M_{z1} and more accurate phases for all components.

In summary, most codes underpredict the amplitudes of most components of force and moment for Propeller 4661 and overpredict the amplitudes at 1xBF and 3xBF for Propeller 4119.

PROPELLERS 4990 AND 5168 ON AN INCLINED SHAFT

Calculated and measured[*] spindle torques are compared in Figures 10 and 11 for Propellers 4990 and 5168. The same grid sizes were used for both propellers, and the grid sizes are given in Table 10. The hub extended downstream of the propellers for the spindle torque measurements, as shown in Figure 12, so PROPCAV was run using the

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[*]   The measurements of spindle torque were taken recently by Martin Donnelly and Stuart Jessup of NSWCCD and should be considered preliminary.

IHUB=3 input option, which has a cylindrical hub extending upstream and downstream without a fairwater on either end. PROPCAV was also run with no hub present. MPUF-3A was run including images for the hub. All values of spindle torque presented are due to the loading on the blade, excluding the contribution of loading on the inclined hub or shaft[*].

Table 10. Grid sizes used for Propellers 4990 and 5168.

	MPUF-3A	PROPCAV
Number of panels across span	18	20
Number of panels across chord	20	60
Number of time steps per revolution	60	60
Spacing across span	half-cosine	half-cosine
Spacing across chord	cosine	cosine

PROPCAV calculations agree well with the measurements for Propeller 5168. For Propeller 4990, PROPCAV predicts the mean spindle torque accurately, but underpredicts the peak-to-trough fluctuations. Excluding the panels on the hub causes the peak in spindle torque to occur at a smaller blade angle than 90 degrees. Otherwise, the presence of the hub panels has a relatively small effect on the spindle torque acting on the blades.

MPUF-3A overpredicts the peak-to-trough fluctuations for Propeller 5168 and underpredicts the fluctuations for Propeller 4990. MPUF-3A accurately predicts the depth of the trough in spindle torque near 270 degrees, for Propeller 4990 and overpredicts the depth of the trough for Propeller 5168.

The MPUF-3A calculations shown in Figures 10 and 11 include the effect of shaft inclination on the propeller wake. However, the tip vortices were constrained to wrap around the extension of the hub aft of the propeller during the experiment, as shown in Figure 12. MPUF-3A may overpredict the amount of wake inclination because the constraining effect of the hub extension is not considered by the wake alignment routine. Therefore, MPUF-3A was re-run for Propeller 5168 using a propeller wake that was not

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[*] The version of PROPCAV from UT/Austin gives the spindle torque due to the loading on both blades and hub. Scott Black of NSWCCD modified PROPCAV to print the separate contributions of the blades and hub.

inclined off of the shaft axis, and the results are shown in Figure 13. Removing the inclination of the wake did not improve the agreement between calculations and measurements. Therefore, the constraint imposed by the hub extension on wake inclination does not appear to explain why MPUF-3A overpredicts the depth of the trough in spindle torque at 270 degrees for Propeller 5168.

Inclining the propeller wake off-axis probably increases the first harmonic of induced velocity at the propeller. Induced velocities usually reduce the angle of attack, so inclining the propeller wake reduces the first harmonic amplitude of spindle torque from $M_{y1}=0.00391$ to 0.00375. The calculated value of M_{y1} agrees better with the measured value of 0.00322, when the propeller wake is inclined off-axis, for Propeller 5168.

There was a sleeve surrounding the rotating upstream shaft for the wake survey but not for the spindle torque measurements. The sleeve increased the diameter of the upstream shaft from approximately 35.1% to 45.1% of the hub diameter. It was expected that the wake deficit of the shaft would be wider and deeper for the wake survey, which would make the calculated M_y too large near TDC $\left(\theta_p = 0°\right)$ and the M_y curve too broad near TDC. However, both codes underpredict M_y near TDC for Propeller 4990. It is therefore expected that the presence of the sleeve is not the primary cause of the differences between calculated and measured M_y near TDC.

CONCLUSIONS AND RECOMMENDATIONS

PROPCAV appears to use an $O(2)$ accurate finite difference scheme to compute the apparent mass force. It is recommended that an $O(4)$ accurate scheme be implemented, to achieve the same order of accuracy used by PUF-2 for calculations of the apparent mass force. This is probably important for design applications that consider the higher harmonics of unsteady forces.

The current versions of MPUF-3A and PROPCAV can accept harmonics of wake no higher than 15xSF and 19xSF, respectively. This is acceptable for many design applications, where the goal is given at 1xBF and 2xBF for a five-bladed propeller. However, much higher harmonics of wake need to be input for some important other design applications, so it is recommended that the highest harmonic of wake be increased.

MPUF-3A uses the ITTC formula for C_f to compute the viscous drag coefficient. However, the ITTC formula overpredicts the flat plate friction coefficient for

$R_n < 2 \times 10^7$, because it is actually a model-ship correlation line, not a friction coefficient. It is recommended that the ATTC formula be used instead, since the ATTC formula is the true friction coefficient for flat plates. It is expected that changing from the ITTC to the ATTC coefficient would reduce the mean torque when the Reynolds number is low and have negligible effect on the unsteady blade loads.

There were few consistent trends in the comparisons of calculations to measurements. For example, most codes underpredict the amplitudes of most load components for Propeller 4661 and overpredict the amplitudes at 1xBF and 3xBF for Propeller 4119. Also, MPUF-3A underpredicts the phase for Propeller 4119 and slightly overpredicts the phase of most components for Propeller 4661. The codes that used an inclined wake model (PUF-2IS and MPUF-3A) did not perform consistently better than codes that did not use an inclined wake model (PUF-14 and PROPCAV), for Propellers 4661 and 5168.

No one code stood out as being significantly better than the others for most test cases. However, if one has to pick a code to use, PUF-2 and PROPCAV appear to be the best codes on average for predicting blade frequency thrust and torque. MPUF-3A overpredicts amplitude and underpredicts phase for several harmonics of thrust and torque, and PUF-14 overpredicts phase. MPUF-3A and PROPCAV appear to be the best codes on average for predicting the first harmonic of blade loads for propellers on an inclined shaft. PROPCAV predicted spindle torque better than MPUF-3A for Propeller 5168. It is recommended that future versions of PROPCAV print separately the contributions of the hub and blade panels to the blade loading.

It was noted previously that some codes underpredicted the amplitudes of most components, for Propeller 4661 on an inclined shaft. One way to quantify the amount of the underprediction is to calculate the average C/M for each code by averaging C/M for F_{x1}, M_{z1}, F_{z1}, and M_{x1} for Propeller 4661. The average C/M is 0.85 for PUF-2IS, 0.92 for PUF-14, 1.00 for MPUF-3A, and 1.04 for PROPCAV. PUF-2IS underpredicts the first harmonic loads by 15%, so a designer may be able to improve his predictions by multiplying the calculated first harmonic amplitudes by 1.15. Similar factors could be used for the other codes based on the average C/M for that code. MPUF-3A would require no correction factor. The factors are to be applied to the amplitude of the first harmonic when nondimensionalized using $\rho n^2 D^4$ for forces and $\rho n^2 D^5$ for moments.
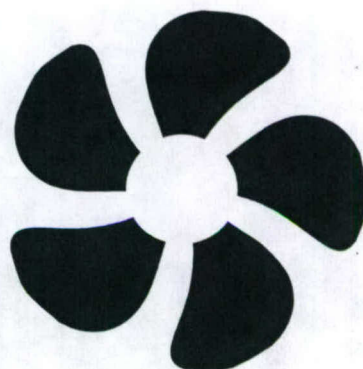
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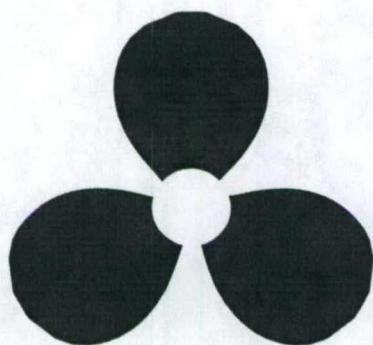
Model 4119
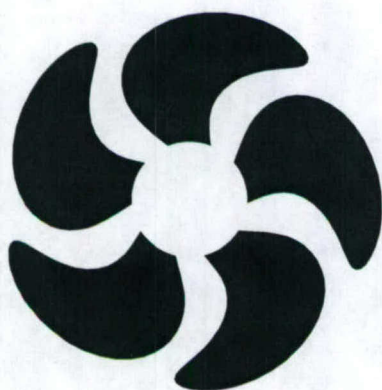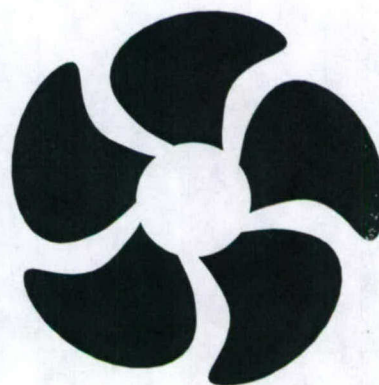
Model 4661

Model 4990

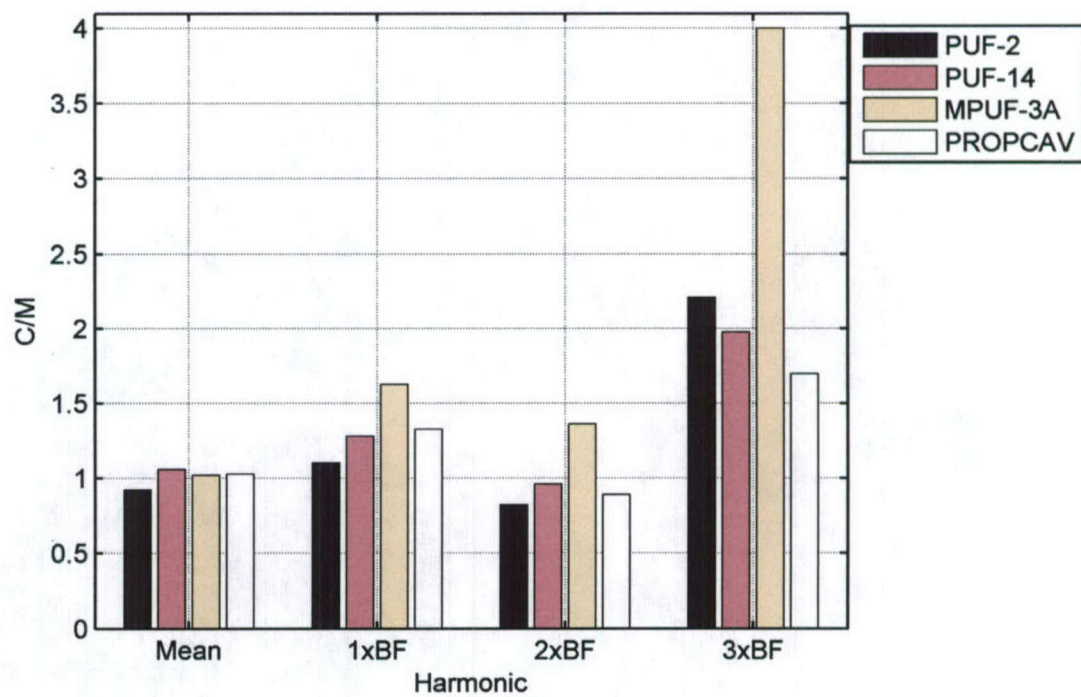Model 5168

Figure 1. Axial view of propellers.

Figure 2. Thrust amplitude ratios for Propeller 4119 in a three-cycle wake.
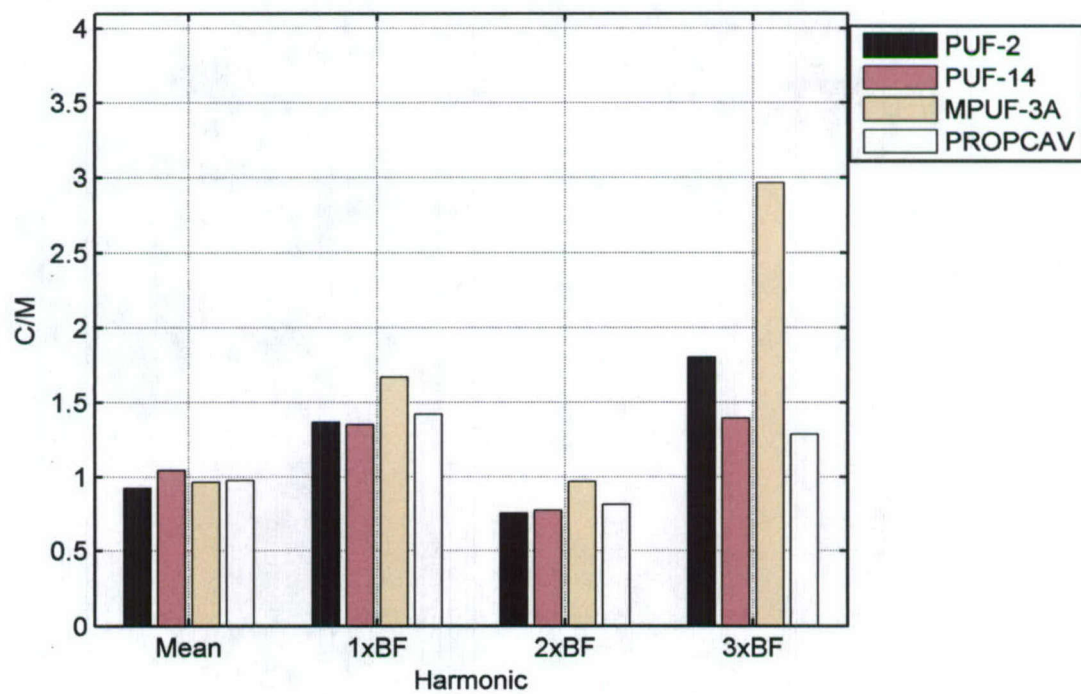

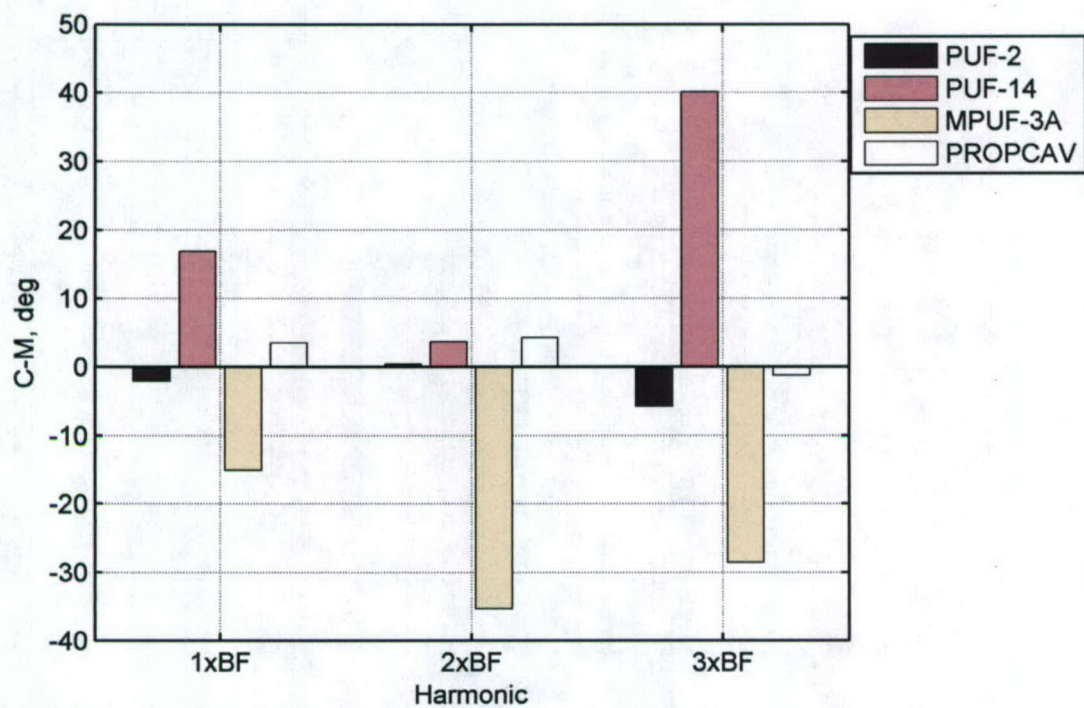Figure 3. Torque amplitude ratios for Propeller 4119 in a three-cycle wake.

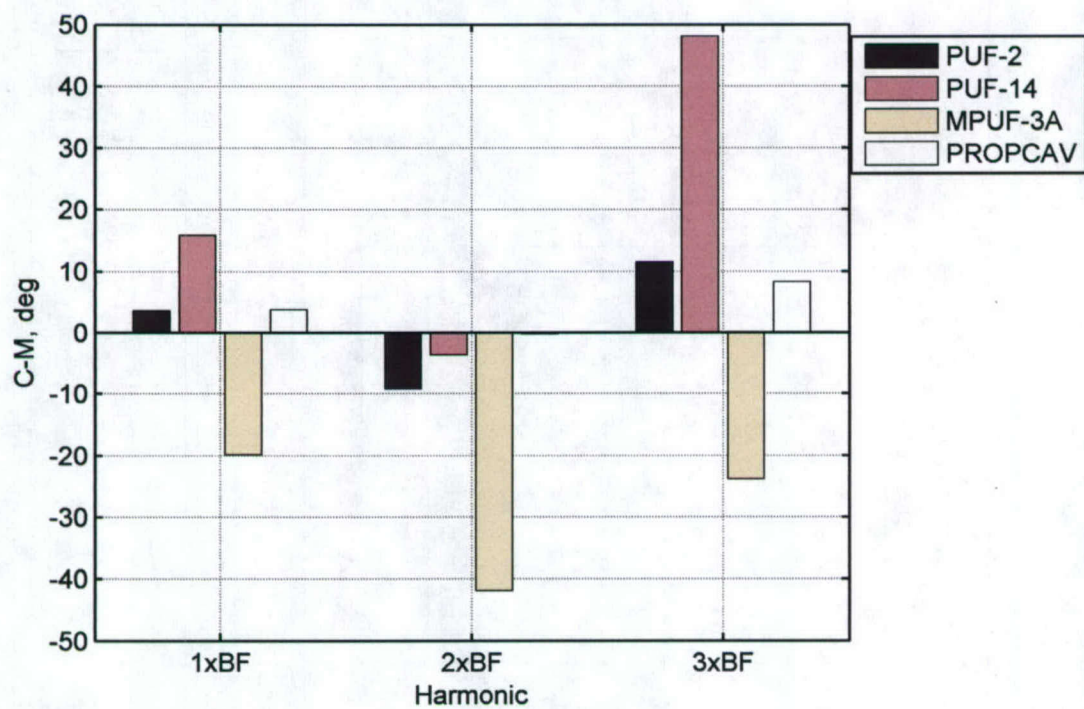Figure 4. Thrust phase differences for Propeller 4119 in a three-cycle wake.

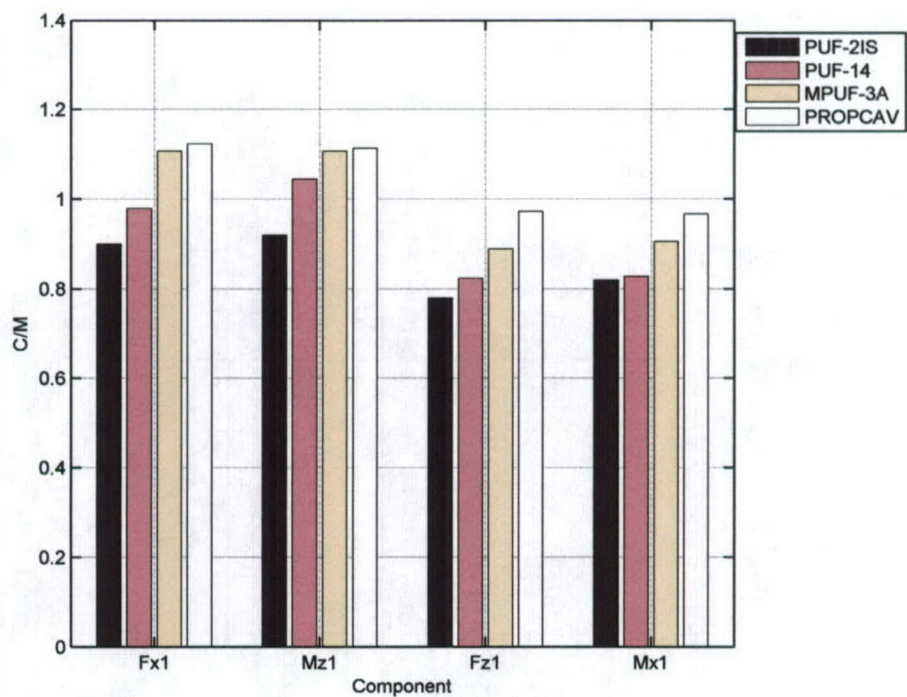Figure 5. Torque phase differences for Propeller 4119 in a three-cycle wake.
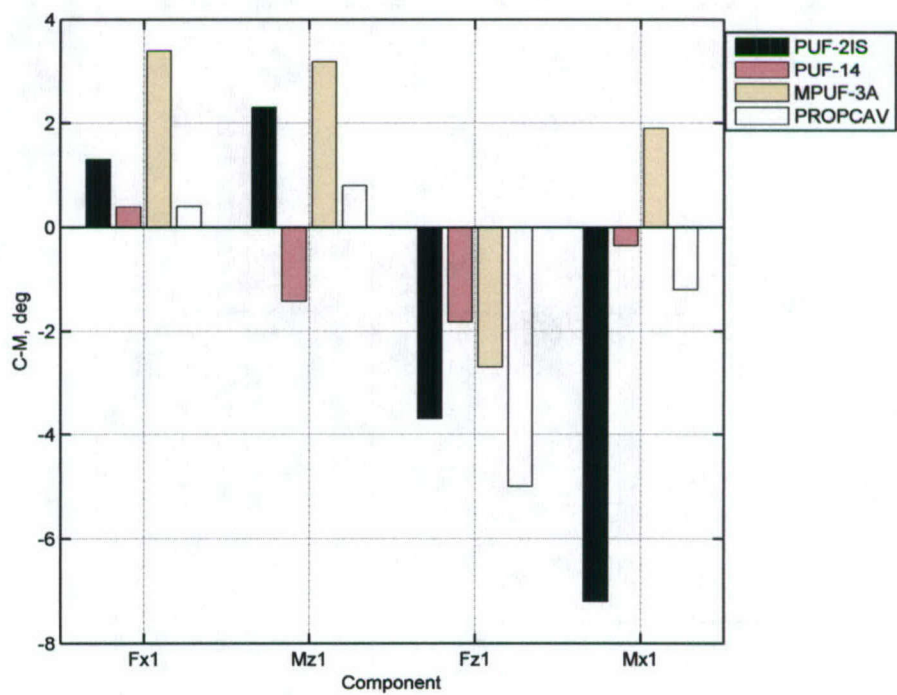
Figure 6. Amplitude ratios for Propeller 4661 with a 10 degree shaft angle.

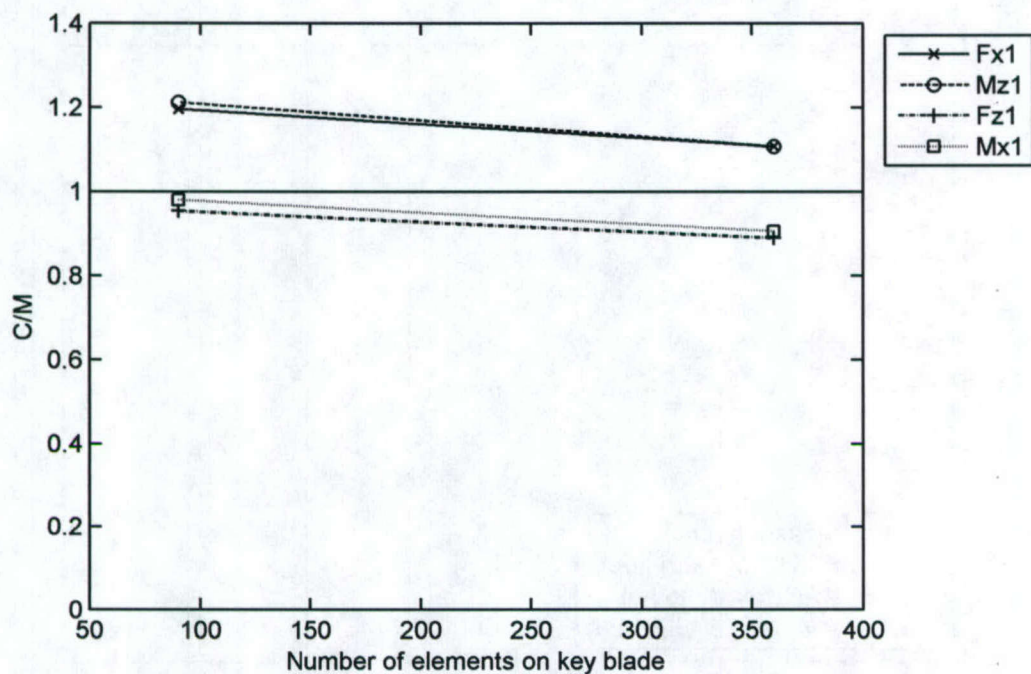Figure 7. Phase differences for Propeller 4661 with a 10 degree shaft angle.

Figure 8. Effect of grid size on amplitude ratios for MPUF-3A and Propeller 4661 with a 10 degree shaft angle.
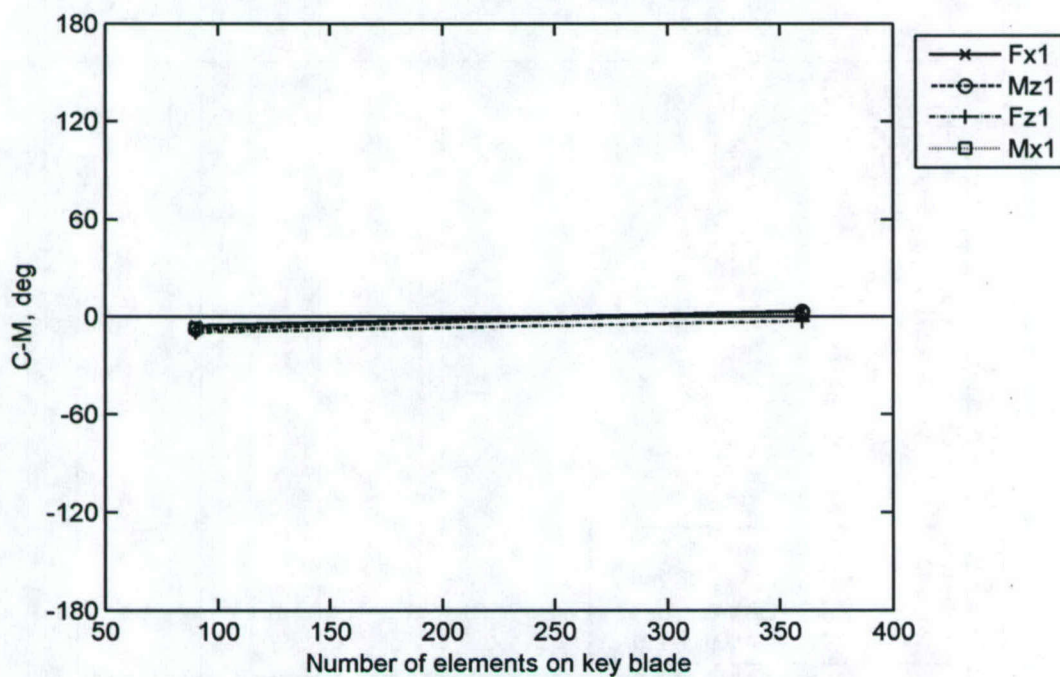

Figure 9. Effect of grid size on phase differences for MPUF-3A and Propeller 4661 with a 10 degree shaft angle.
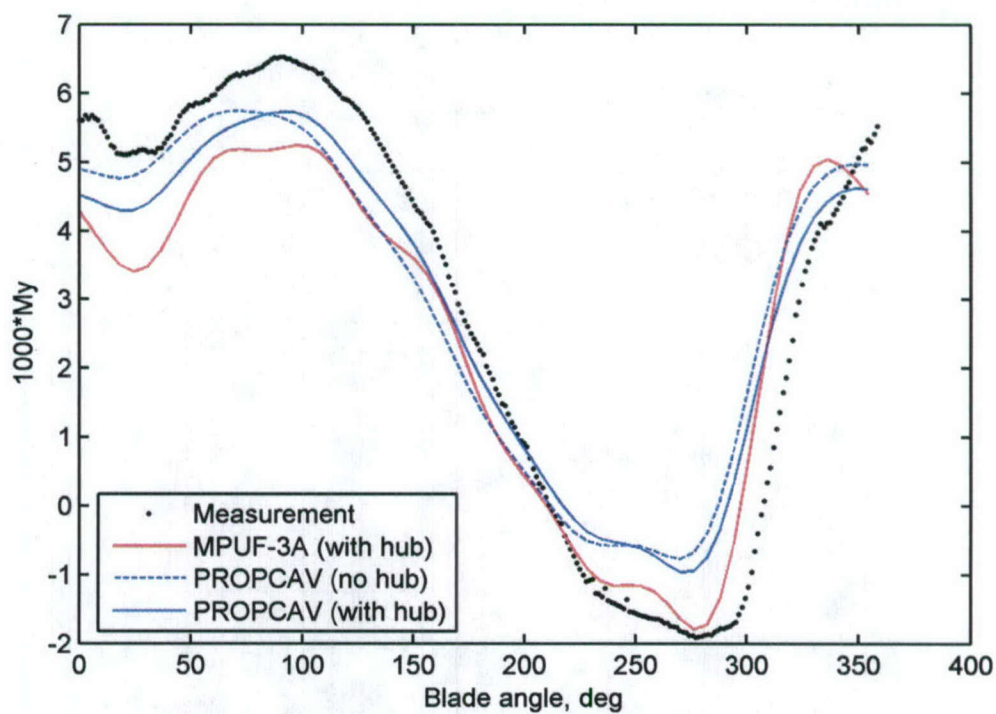
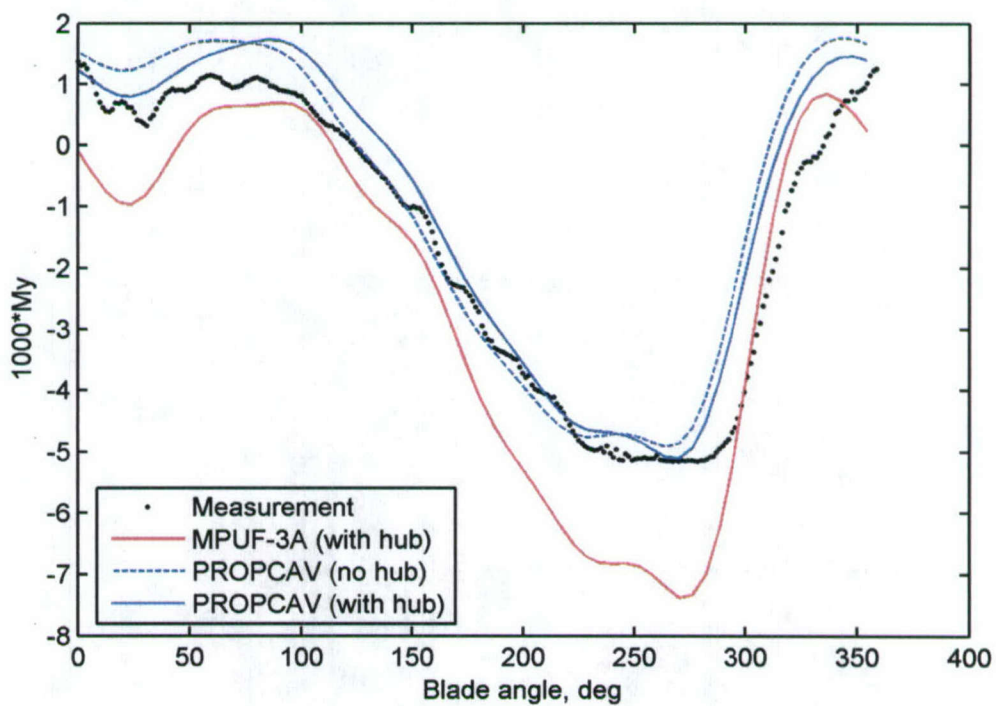Figure 10. History of spindle torque for Propeller 4990 at J=1.25 in 36" water tunnel.

Figure 11. History of spindle torque for Propeller 5168 at J=1.25 in 36" water tunnel.
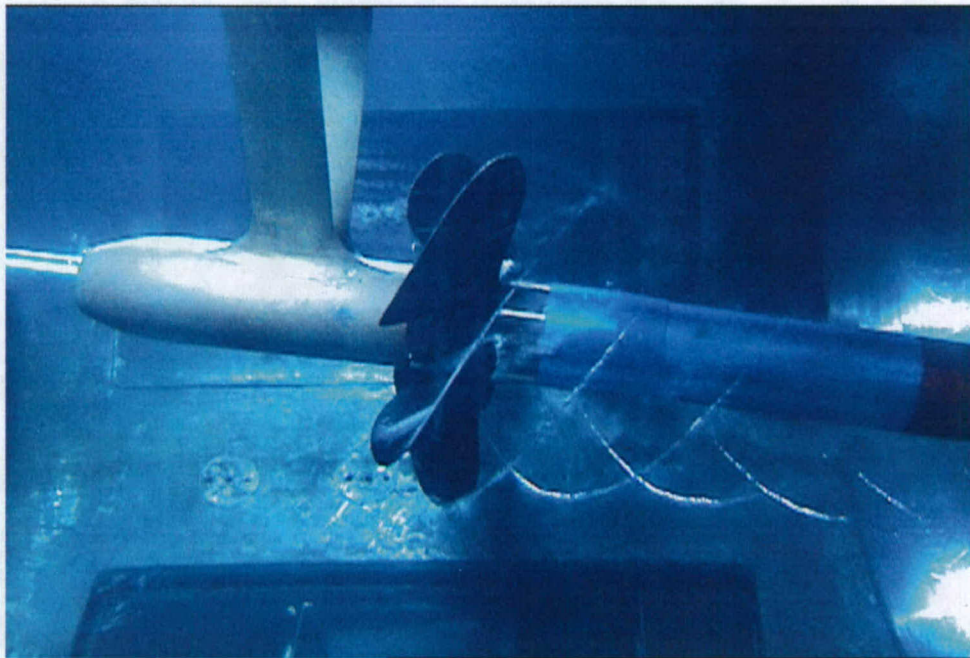
Figure 12. Extension of hub downstream of propeller for spindle torque measurements on Propellers 4990 and 5168 in 36 inch water tunnel.
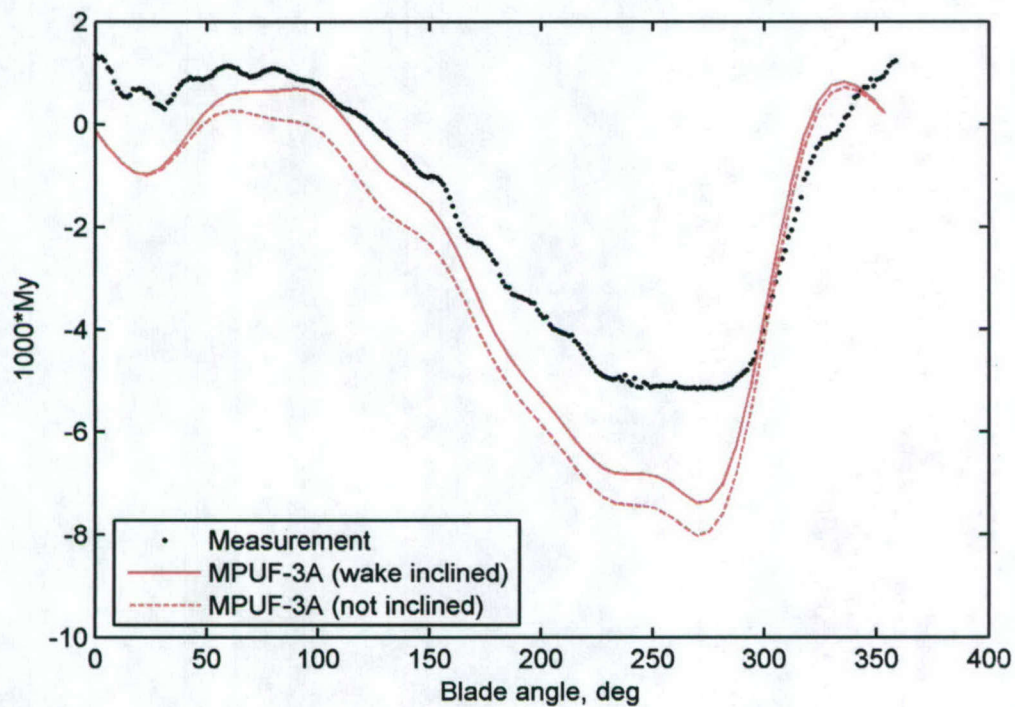

Figure 13. Effect of inclined shaft wake model on MPUF-3A predictions of spindle torque for Propeller 5168 at J=1.25 in 36" water tunnel.

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